Measuring the electron edm using laser-cooled Cs atoms in optical lattices

Cheng Tang
Teng Zhang
Kunyan Zhu
Neal Solmeyer
Fang Fang
David S. Weiss

Supported by the NSF
Projected Sensitivity

Electric field $E \sim 150 \text{ kV/cm}$

Cs enhancement factor $R=120.5$ \footnote{Known to <1%}

Coherent evolution time $\tau \sim 3$ seconds

Total experiment time $T/2 \sim 24$ hours

Total number of atoms per shot $N_{Cs} = 1 \times 10^8$

Shot noise limited sensitivity to electron EDM is:

$$\delta d_e = \frac{\hbar}{4ER\sqrt{NT\tau}} = 2.4 \times 10^{-30} \text{ } e \cdot cm$$

→ possible improvement by a factor of \sim 40
Outline

• Overview of our eEDM measurement
• Atom processing in our apparatus
• State preparation and detection
• Atomic magnetometry (vector light shifts)
• EDM spectroscopy in large E fields
• Sensitivity, noise and systematic effects
• Status
The EDM Measurement

\[
\psi = \begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
1 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\]

Coherent transfer

Evolve

\[
\begin{bmatrix}
\exp\left(+i \frac{3(dE + \mu B)}{4\hbar} \tau\right) \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\]

Coherent transfer back

Final \( m_F=0 \) pop.

Our sensitivity: \(|dE|\sim h\times20 \text{ nHz}\)

F=3 ground hyperfine state
Multi-photon “rf” pulses

With three frequency components we expect to achieve >99% fidelity in a few cycle long pulse.
Processing the atoms

Capture and cool atoms in 1064nm 1D optical lattices made of build-up cavities

Launch ~10x to fill up the lattices

lattice-guided ~90cm launch

Zeeman slower

Oven


MOT

Electric field plates, top view

Glass field plates allow 3D cooling and fluorescence imaging. *In situ* interferometric measurements of plate flatness imply highly uniform electric fields.
The experiment’s core

Friction-mounted; handle baking

R=20cm
Atoms in the measurement region

~15 \( \mu \text{K} \) trapped atoms
Atoms are optically pumped to $|4,-4\rangle$ with 99.97% fidelity, and are then transferred to $|3,0\rangle$ by microwave pulses.
Uniformity of microwave pulses

$\lambda_{\mu w} \approx 3.26 cm$
Microwave transitions

Using five adiabatic rapid passage pulses we have transferred Cs atoms from $|4,-4\rangle$ to $|3,0\rangle$ with 99.5% fidelity in 10ms. Microwaves also allow state-selective fluorescence detection.
Fluorescence detection system

Imaging system (top view)

Low-noise, nonmagnetic photo-detector array
State-selective fluorescence detection

We map out the complete picture of atoms in the F=3 hyperfine ground state in <50 ms.

The sequence is repeated for all 7 sublevels.
The Hanle measurement procedure

(using Cs F=3 hyperfine ground state; $m_F=+3, +2, \ldots, -3$)

The Hanle measurement procedure

(using Cs F=3 hyperfine ground state; $m_F=+3, +2, \ldots, -3$)
The Hanle measurement procedure
(using Cs F=3 hyperfine ground state; $m_F=+3, +2, \ldots, -3$)

\[
\begin{bmatrix}
0 \\
0 \\
0 \\
0 \\
1
\end{bmatrix}_y \Rightarrow \frac{1}{8} \begin{bmatrix}
1 \\
\sqrt{6} \\
\sqrt{15} \\
\sqrt{20} \\
\sqrt{6} \\
1
\end{bmatrix}_z \Rightarrow \frac{1}{8} \begin{bmatrix}
1 \cdot e^{-3i\phi} \\
\sqrt{6} \cdot e^{-2i\phi} \\
\sqrt{15} \cdot e^{-i\phi} \\
\sqrt{20} \cdot e^{0i} \\
\sqrt{15} \cdot e^{+i\phi} \\
\sqrt{6} \cdot e^{+2i\phi} \\
1 \cdot e^{+3i\phi}
\end{bmatrix}_z \Rightarrow N_{m_F}(\phi)
\]

\[\phi = \omega_L t, \omega_L = \omega_B + \omega_U\]

The Hanle measurement procedure
(using Cs F=3 hyperfine ground state; $m_F=+3, +2, ..., -3$)

\[
\begin{pmatrix}
0 \\
0 \\
0 \\
0 \\
0 \\
1
\end{pmatrix}_y \Rightarrow \frac{1}{8} \begin{pmatrix}
1 \\
\sqrt{6} \\
\sqrt{15} \\
\sqrt{20} \\
\sqrt{15} \\
1
\end{pmatrix}_z \Rightarrow \frac{1}{8} \begin{pmatrix}
1 \cdot e^{-3i\phi} \\
\sqrt{6} \cdot e^{-2i\phi} \\
\sqrt{15} \cdot e^{-i\phi} \\
\sqrt{20} \cdot e^{0i} \\
\sqrt{15} \cdot e^{+i\phi} \\
\sqrt{6} \cdot e^{+2i\phi} \\
1 \cdot e^{+3i\phi}
\end{pmatrix}_z \\
\Rightarrow N_{m_F}(\phi) \rightarrow \langle S \rangle = \frac{1}{m_p} \frac{\sum m_F \times N_{m_F}}{\sum N_{m_F}} = \begin{cases} 
\sin(\phi), \text{in } X \\
\cos(\phi), \text{in } Y
\end{cases}
\]

$\phi = \omega_L t, \omega_L = \omega_B + \omega_U$
Sensitive atomic magnetometry

Using spin-polarized cold atoms we have actively cancelled the magnetic fields in the science chamber to a level of ~3 \( \mu \)G (no gradient cancellation yet)
Implementation of 3 bias and 5 gradient cancellation coils

Use 8 homemade current sources, ~20 μA output, with 200 nV/Hz^{1/2} noise, and 30 μV step size
B-field cancellation and shields
Vector light shifts

Vector light shifts (VLS’s) are ac-Stark shifts proportional to an atom’s magnetic quantum number. They act on atoms like fictitious magnetic fields:

\[ \nu_V = \alpha_V U m_F \cdot i(\epsilon^* \times \epsilon) \cdot e \]

VLS issues can be minimized by designing experiments with \( k \perp e \), or using pure linear polarization \( (\epsilon^* \times \epsilon = 0) \)

VLS’s are linearly sensitive to linear polarization imperfection. We have use them to demonstrate unprecedentedly accurate absolute measurements of linear polarization.
The optical lattice setup

3-axis precision alignment of Brewster plates

Indium sealed vacuum windows

Solmeyer, Zhu and DSW, Rev. Sci. Instrum. 82, 066105 (2011)
Measurement of large VLS

When the +X cavity polarization is misaligned, $\omega_L \approx \omega_U$, halving the lattice power halves the precession frequency.

The oscillations quickly damp out because trapped atoms experience different average VLS.

VLS at U=100 $\mu$K

$\nu_V = 792(30)$ Hz

$\theta = 7.3(3) \times 10^{-3}$ rad
**Measurement of high quality linear polarization**

Signal comes from a uniform effective magnetic field combined with lattice beam linear polarization imperfections of $\sim 2 \times 10^{-8}$ in fractional intensity.

$$\theta_{+X} = -1.50(5) \times 10^{-4} \text{ rads}, \quad \theta_{-X} = +1.33(5) \times 10^{-4} \text{ rads}$$

Physics of Cs atoms in large E fields

The EDM-sensitive states are “protected” from transverse magnetic fields:

\[ |E_{+3} - E_{-3}| \propto \left( \frac{g_F \mu_B B_\perp}{\frac{1}{2} \alpha E_Z^2} \right)^6 \]
Transverse Field Requirement

These vector light shifts are sufficiently small as long as $E > 50\text{kV/cm}$
Noise considerations

• **2 parallel traps** →
  Insensitive to uniform B field fluctuations

• **Reversal of E-field polarity** →
  Insensitive to B field gradients

• **Magnetic noise:**
  - Johnson noise (Glass/ITO/plastic, Ti/Cu)
  - Passive shielding + active B control
  - Thermoelectric currents (limiting Rs)

• **Trapping light related noise:**
  Scattering rate (FORT), VLS (linear polarization), tensor shifts (stabilized intensity)

• **Preparation and measurement noise:**
  Normalized EDM signal, high SNR detection
Potential systematic effects

(1) Leakage currents:
   1~2 pA/kV (measured)
   connect both ends of the plates
   center lattices w.r.t. the plates

(2) B-field gradient + Non-uniform E-field +
    imperfect E-reversal:
    Plate wedge $\leq 1.5 \times 10^{-4}$ (measured)
    E-reversal $\sim 2 \times 10^{-5}$ (achieved)
    B-gradient $< 140$ nG/cm (achievable)

(3) Linear Stark interference:
    lattice beam imbalance $\sim 2 \times 10^{-3}$ (achieved)
    $\varepsilon_{\text{lattice}} \parallel \varepsilon_s$ to $10^{-3}$ rad (achievable)

* Many handles, including
  two sets of spatially resolved atoms in opposite E-fields; ultimate check with two alkali species
Status

When turning up the electric fields, electric breakdown destroyed the coating at 10 kV, ~3x lower than the worst case in our early trials.

The design is fixed. New plates are (finally) delivered. We are installing them.

Then all parts of the measurement should be good to go.